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UTILIZATION OF NAVY-GENERATED WASTE OILS AS BOILER FUEL-ECONOMI--ETC(U)

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INTRODUCTION

Significant quantities of waste oils are routinely generated at all Naval shore facilities; the types and quantities generated depend on the particular activities engaged in each facility. These oils may be classified in four broad groups: used lubricating oils, contaminated distillates, ship waste oils, and low flash fuels and solvents. In the past, these materials were disposed of in several ways (e.g., by dumping, for dust control, for fire fighter training, by hauling away by contractor at a cost). These methods vary from little use to counterproductive. Because of the increasingly tighter environmental regulations, dumping and dust control are no longer allowed. Since these materials are combustible and have practically the same energy content or heating value as regular fuel oils of comparable densities, their substitution as boiler fuels is an attractive alternative disposal method. The advantages of this method are: (1) elimination of the costs and work involved in disposal and (2) reduction of Navy fuel requirements by utilizing the available energy - thereby conserving energy resources.

The objective of this study was to develop guidelines for burning Navy-generated waste oils in the low pressure boilers typically used at shore facilities. The ultimate goal is to burn all the waste oils at the source of generation where economical. To determine the possible savings, estimates of waste oil generation by the Navy must be made first. Then laboratory and boiler firing tests will be conducted to determine the techniques and operational limits in waste oil boiler firing. Guidelines for implementing waste oil burning in Navy boilers will be developed as the final output.

As a part of the overall effort, this document describes the results of a feasibility study of utilizing the Navy generated waste oils in boilers.

LITERATURE ON WASTE OIL UTILIZATION

Studies on waste oil burning have appeared in the literature only during the past decade, and the work reported has been primarily concerned with firing of used lubricating oils. Examples are Reference 1's discussion of fuel for a municipal incinerator and Reference 2's on cement kiln. Mostly, the studies described firing of blends in different proportions with regular fuel oils as boiler fuels. Because of the Navy's interest, only the results of boiler firing are discussed here.

The earliest work on boiler firing of used lubricating oils is probably that reported in Reference 3. The observations of participating oil companies (Humble, Shell, American, Gulf, Mobil) are summarized, and recommendations are made in this report. Generally, used lubricating oils, either straight or in blends with regular fuel oils of different proportions, can be satisfactorily fired in boilers, but the maintenance requirements are higher for blends with the higher concentration of used lubricating oil. Problems that may be expected include: fine lint buildup in barrels and nozzles, which are hard to clean; substantial ash buildup in the fire box, deposits on boiler tubes, and flyash, which are attributable to the additives in the oils; rise in flue gas temperature due to deposit buildup on heat transfer surfaces. In a test when a blend of 25% used lubricating oil (containing 1.12% lead) and no. 2 fuel oil was fired at 3 to 4 gph, up to 28% of the lead came out of the stack. In another test, when a blend of 5% used lubricating oil (containing 1% lead) and no. 6 fuel oil was fired at 147 gph, up to 50% of the lead came out of the stack. In general, the ground level lead concentrations estimated were all within safety limits. To minimize maintenance, it was recommended for boiler firing that less than 25% of the blend be used lubricating oils.

During the period 1968-1972, the Army burned approximately 40,000 gallons of used lubricating oils each year in a boiler plant (60 MB/hr, water tube boiler with steam atomization burner) at Aberdeen Proving Ground (Ref 4). This oil was introduced into the fuel system by simply dumping it into the no. 6 fuel oil tank at a proportion of 1:3 (or 25% used lube oil in the mixture). Since no deliberate blending or mixing was attempted, the exact concentration of the blend could vary considerably. No difficulty was encountered, however. In 1972, when low sulfur oil had to be used in order to limit the SO_2 emissions, two series of short-term tests were conducted burning no. 2 and used lube oil blends using a rotary cup burner in a 5.4 MB/hr fire tube boiler (Ref 5). No stack emission problem was encountered for blends that contained up to 27% used oil.

A more systematic test series was conducted by the Air Force (Ref 6). Waste oils containing aviation piston engine oils, synthetic turbine lubricant, hydraulic fluid, Stoddard solvent, and other fuels were mixed with no. 2 and no. 6 fuel oils at concentrations of 0, 0.1, 1, and 10%. Then each of these blends was fired for 30 minutes to determine the firing characteristics. No difficulty was encountered, and no ill effects (e.g., emissions, corrosions, degradation of boiler systems) were observed. A series of 2- to 3-hour tests were then conducted at 5% concentration. Satisfactory firing was achieved, and no increase in particulate emisssions were measured. As a result, long-term in-service boiler tests were recommended. Tests of this nature were conducted at three Air Force bases (Ref 7). Up to 26% used lube oil in no. 2 oil, 6% JP-4 in no. 5 oil, 16% JP-4 in no. 2 oil, 4% and 11% of 50/50 JP-4/used lube oil, respectively, in no. 2 and no. 5 oils were tested. Results showed that relatively clean-burning fuel (e.g., JP-4) mixed in relatively dirty fuel (e.g., no. 6) would not adversely affect the emissions allowed by the regulations. But relatively dirty fuel (e.g., used lube oil) mixed in clean fuels will significantly increase the particulate emissions although the emissions are still below standards described by the regulations. In all, the combustion performance was either the same or improved.

The Navy recognizes the large quantities of waste oils it produces and the potential of using them as supplemental boiler fuels. A guideline was therefore developed for handling and burning oily wastes (Ref 8). In this guideline, direct blending of petroleum base waste oils (halogen free, water and sediment <2%, sediment <0.5% by volume) into clean fuel oils is discussed, but no specific information on the allowable waste oil concentrations is given. The procedure for handling waste oils consists of first storing the oil in a holding tank to allow gravitational separation of water and solid materials. The "cleaned" oil may be blended directly into the fuel tank or introduced into the fuel line by an in-line system using two tanks for handling waste oils. The latter is recommended and is illustrated schematically in Reference 9.

Disposal of used lubricating oils has been studied also by western European countries (Ref 10). For economic reasons, the use of used lubricating oils as fuels has been recommended in order to recover the heat value and to minimize disposal costs.

Scattered, fragmented information on waste oil boiler firing may be found, but it is also limited to data on the blending of low concentrations of used lubricating oil with regular fuel oils. Low concentration blending is sometimes impractical because of the high waste oil generation rates relative to the low energy requirements at certain locations. In view of this and the wide range of waste oils produced by Naval shore facilities, a more thorough study of the problem is in order for full utilization of the locally generated waste oils by the Navy.

To make such a study economically attractive, an estimate of the waste oils generated by Naval shore facilities is an important basic step.

WASTE OIL GENERATION BY NAVAL SHORE FACILITIES

The information on the waste oils generated at Naval shore facilities will serve as the basis for assessing the economic potential of using these oils as supplementary boiler fuels. Funding limitations make it necessary that only an estimate based on data from available literature be made here.

Data on Waste Oil Generations

In 1972 ESSO Research and Engineering Company under contract with Naval Supply Systems Command conducted studies on oily wastes* generated at Naval shore facilities. Seven Navy areas were surveyed during this contract, and the types, quantities, and characteristics of the Navy oily wastes were identified (Refs 11 through 17). Based on the results of these surveys, the waste oil generations after 1975 were then estimated. The results extracted from these studies are summarized in Table 1. Under a similar contract with Naval Facilities Engineering Command, Exxon Research and Engineering Company (formerly ESSO) conducted a series of studies on oily wastes generated at 17 Navy bases (Refs 18 through 34). The results extracted from these studies on prediction of waste oil generations for 1980 are summarized in Table 2.

The data in Tables 1 and 2 cover a wide range of Navy activities and, therefore, may be considered representative of the overall picture of waste oil generations by Naval shore facilities. These data are used as the basis for estimating the Navywide waste oil generations discussed here. In order to remove the dependence of the data on the particular locations, the data in Tables 1 and 2 are summed together in Table 3.

*The oily wastes referred to here are basically water which is contaminated by oils. Waste oils are actually mixtures of oils and other combustible liquids which contain very litte water.

The overall results from References 11 through 34 may be summarized as follows:

1. The waste oils generated by Naval shore facilities are predominantly those recovered from bilge and ballast water of ships. This oil is primarily the fuel oil used by a particular ship and, in general, resembles light fuel oils (e.g., diesel fuel marine or DFM) except that it is contaminated by the other oily materials present on board the ship. These types of oils are usually very dark in color.

2. Used lubricating oils and similar materials discarded by transport and ships rank the next highest in quantity. This material resembles heavy fuel oils.

3. High flash fuels rank third in quantities generated. This material consists primarily of contaminated fuels (e.g., JP-5, diesel fuels, kerosene) and is a light fuel.

4. Solvents and low flash fuels are produced in the least quantities. Solvents sometimes contain halogenated compounds, which also may have low flash points. Low flash fuels require special attention to fire in a boiler. Both the solvents and the low flash fuels are considered hazardous to fire in boiler and therefore are undesirable as boiler fuels.

When one considers the waste oils as boiler fuel, the data in Table 3 may be further simplified by regrouping the types into three categories as follows:

1. Light waste oils: Oils recovered from bilge and ballast waters and high-flash-point contaminated fuels, representing approximately 87% of the total waste oils generated.

2. Heavy waste oils: Oils from transport and shops, tank cleanings, and turbine drainings, representing approximately 9% of the total waste oils generated.

3. Others: Low flash point contaminated fuels and used solvents, representing the balance, or approximately 4%, of the total waste oils generated.

Categories 1 and 2 above are considered safe and suitable for boiler fuels. Category 3, because of the nature of the materials is considered undesirable as boiler fuels.* Thus, of all the waste oils the Navy generates, more than 96% of them may be regarded as potential boiler fuels.

*Recycling used solvents and using low flash fuels for fire-fighter training offer a productive means of disposing of these materials.

Fuel Consumption by Navy Shore Facilities

Fuel oils are the first substitutes for natural gas and liquefied petroleum gases during shortages. Waste oils are considered suitable substitutes or supplements to all these fuels in such a situation. In this sense and with the intent to contrast the significance of the waste oil data presented earlier, data on the consumption of natural gas, liquefied petroleum gases, and fuel oils (GLO) for FY-77 were extracted from DEIS-II (Defense Energy Information Service - Navy) files for the activities listed in Tables 1 and 2. The results are given in Table 4. In the last column of Table 4, the ratios "Waste oil generation/GLO" represent the percentages of GLO requirements at each activity that may be substituted by the waste oils generated at that activity. The large scatter of the numbers in this column reflects the greater use of other forms of energy (electricity, coal, purchased steam) than GLO at some activities. For example, in the Canal Zone, GLO is not used at all for energy but waste oils are generated because of the activities involved. In this case, burning waste oil at other locations must be considered. Overall, the last row of Table 4 shows that these activities may substitute the waste oils they generate for about 13% of their GLO requirements. This figure is sizeable, and the potential for waste oil utilization must not be ignored.

An Estimate

The total energy used by all Naval shore facilities during FY-77 is summarized in Table 5. The GLO usage (sum of the first three rows) is 73,592,936 MBtu, which represents 46% of the total energy used and 43% of the total fuel bills paid. Comparing this figure with the GLO total in Table 4 (28,206,588 MBtu), it can be inferred that on the basis of GLO consumptions 38% of the Naval shore facilities have been surveyed for waste oil generations (see Table 6). This means that, on the average, more than one-third of the Naval shore facilities generate waste oils which are about 13% (Table 4) of their local GLO requirements.

The waste oil generation data presented here appear to be the only information available. These data and the Navywide GLO consumptions will be used to establish the upper and lower limits of Navywide waste oil generations. The lower limit is obtained by assuming that all the waste oils generated by the Navy are from only the facilities listed in Tables 1 and 2. The upper limit is obtained by assuming that all the Navy shore facilities generate waste oils at the same average rate (12.8%) of local GLO consumptions as the facilities listed in Tables 1 and 2 do. The results of these calculations and the estimated worth of these oils are presented in Table 6. Clearly, if the Navy fully utilizes their waste oils, between $8.7M/yr and $22.7M/yr savings can be realized.

A CASE STUDY

The question asked in this study is: How can waste oils be gainfully utilized? The following is an example which proposes burning the waste oils generated at one location in the boilers at a nearby Navy facility. Specifically, the waste oils generated at San Diego Naval

Station (SDNS) are considered as fuels for the boilers at Miramar Naval Air Station (MNAS). Since realistic figures from records are used, the economic advantages are readily demonstrated in this example.

Large quantities of waste oils, similar in consistency to diesel fuels, are generated from ship-related operations at SDNS. They are usually dark in color and contain less than 2% water and sediments. Some data on the waste oils generated were obtained from Oil Recovery Operations Division, SDNS. The figures for FY-77 and FY-78 are tabulated in Table 7. These data show a significant increase in the annual waste oil generations at the station. These waste oils have been sold to outside contractors through the Defense Property Disposal Office for 22.2¢/gal (or $1.63/MB) for FY-77 and 25.3¢/gal (or $1.864/MB) for FY-78. On the other hand $3.05/MB was paid by MNAS for diesel fuel no. 2 (DF2) during FY-77. Selling the waste oils to contractors results in losses to the Navy.

MNAS, approximately 15 miles from SDNS, has a year-round demand for low pressure steam. Both interruptible natural gas and light grade fuel oils are used as the primary fuels for the steam boilers. The total energy (all fuels) consumed at MNAS for boilers in million Btu's and the waste oils generated at SDNS are compared in Table 8. The figures show that the waste oils generated at SDNS could approximately meet the energy requirements of MNAS. Since exact matching is not possible, any deficiency in waste oil for MNAS could be easily made up by use of interruptible natural gas. During FY-78, MNAS used some contaminated JP-5 as the boiler fuel at no cost. Because of this and price adjustments on natural gas and DF2, the total fuel bills paid during FY-78 were lower than FY-77 even though the amount of energy used was higher.

An economic analysis is also presented in Table 8. To avoid unnecessary confusion, the net saving to the Navy for FY-78 is not presented. However, the results of this analysis show clearly the economic advantage in utilizing the Navy-generated waste oils rather than selling them to contractors.

WASTE OIL LABORATORY TESTS

As described earlier, results of boiler tests on waste oils in the literature are fragmental in nature. To determine the feasibility of utilizing the Navy's waste oils, systematic tests must be conducted for a range of blends of typical Navy waste oils and conventional fuel oils. Items of interest consist of combustion performance, burner modification requirements, stack emission characteristics, effects on boiler heat transfer surfaces, and handling and storage requirements. To achieve these, laboratory tests were conducted in two steps: (1) systematic boiler testing of waste oil/clean fuel oil blends of a range of concentrations by contract, and (2) boiler testing of selected waste oils at CEL. Only short-term tests of batches of prepared waste oils and their blends were conducted for this study. The details in fuel handling and long term effects will be investigated later, depending on the findings of the present work.

Tests Conducted by Contract

The Navy's waste oils consist of two basic types: light and heavy. The fuel oils used by Navy shore facilities range between no. 2 and no. 6 commercial grade, conventional fuel oils (light and heavy, respectively). Thus, a total of six ways are possible for firing the waste oils with conventional fuel oils: two in burning straight waste oils, and four in burning blends of light and heavy waste oils in light and heavy conventional fuel oils. On this basis, a matrix of 26 waste oil/fuel oil blends was developed for boiler tests. This work was conducted by KVB, Inc., a CEL contractor. Pertinent details are described below.

Test Facility. The facility used for the tests was an 80-hp Scotch dry-back type, firetube boiler using a steam atomizing burner (a Delavan nozzle). Fuel blends were prepared in 55-gallon batches and delivered to the burner by a positive displacement pump. The overall arrangement of the fuel system is shown in Figure 1.

The primary measurements made for the tests described here are continuous monitoring of stack gas emissions. Approximately equal amounts of flue gas samples were withdrawn from three sampling points just upstream of the draft damper where the gas temperature was approximately 500°F. These samples were blended into a single stream which was filtered and then dried by a refrigerator. The following measurements were made using the instruments indicated:

NO: Thermo Electron Corp. chemiluminescent nitric oxide analyzer

CO: Beckman Model 315-B nondispersive infrared analyzer

O_2: Beckman Model 742 oxygen electrolytic analyzer

CO_2: Horiba Model AIA-2 nondispersive infrared analyzer

Smoke: Bacharach smoke spot tester

Sulfur dioxide (SO_2) was not measured because the sulfur content in fuel oils is usually regulated by local authorities, and SO_2 emissions are not strongly dependent on the combustion process. That is, SO_2 emissions can be determined reasonably well from the sulfur content of the fuel oil. In contrast, nitric oxide is strongly dependent on both the combustion process and the nitrogen content of the fuel.

Oils Tested. The oils used for the tests consisted of randomly selected single shipments (not necessarily typical) of:

- Waste Oils:
  - Used lube oil* from diesel service shop (heavy)
  - Ship's waste oil (light)
  - Contaminated JP-5 (Navy aircraft fuel, also light)

*DOD Directive 4165.60 is scheduled for revision to incorporate formal policy on used lubricating oil disposal methods. The current DOD guidance consists of two steps: (1) examine the feasibility of re-refining in order to conserve natural resources, and (2) if re-refining is not economical, use it as boiler fuel in order to recover the energy content. The old methods, such as dust control, are not allowed.

- Fuel Oils:
  - No. 2 (light)
  - No. 6 (heavy)

The properties of these oils were analyzed and are given in Table 9. Note that these oils have similar properties except that:

(1) Contaminated JP-5 has a large amount of water

(2) Used lube oil contains large amounts of trace elements, which are believed to be due to the additives contained in the clean lube oils.

These oils were blended at various concentrations to obtain a matrix of 24 blends as shown in Table 10. Inasmuch as all fuel oils are actually mixtures of various hydrocarbons, test results from this matrix of oil blends should provide adequate coverage to determine the effects of the waste oils.

Test Procedure. Oil blends were first prepared in batches in the mixing tank (Figure 1). When no. 6 oil blends were prepared, they were heated by the drum heater to facilitate pumping. The burner was fired with the blend, and the boiler was allowed to warm up for 15 to 30 minutes. During this warmup period, observations were made of flame stability, combustion rumble, and the operational requirements of the system.

Following the warmup period, the burner was trimmed to the test load, approximately 3.2×10^6 Btu/hr, and a series of tests was performed by systematically varying the excess oxygen dry volume fraction in the flue gas from 1% to 8%. A complete set of data was collected at each excess oxygen setting, including: NO, CO, CO_2, smoke spot number, flue gas temperature, and fuel flow rate. Visual observations of the flame shape and stability, photographs of the flame, and flue gas characteristics were also included.

Upon completion of this series of tests, the excess oxygen was set at approximately 3.5%, and the blend was burned for a period of about 2 hours. A set of data was taken every 30 minutes during this period.

Test Results. To evaluate the performance of firing waste oil/fuel oil blends, the handling requirements, flame characteristics, and stack emissions were observed during the tests. For comparison, similar sets of data (baseline data) were obtained for unblended no. 2 and no. 6 fuel oils. A data summary of all the tests (26 in all) is given in Table 11. The effects of excess oxygen on smoke and NO emissions are shown in Figures 2 and 3.

Based on observations and test results obtained, the following conclusions may be drawn:

1. No apparent problems were encountered in fuel miscibility or pumping and firing any of the fuel blends.

2. Fairly clean firing was achieved with all blends. This included relatively clean nozzle tips, stack gases, and boiler gas-side heat transfer surfaces.

3. The NO emissions were generally reduced in the blends with no. 6 oil and either unchanged or reduced with no. 2 oil. This is believed to be due primarily to the relatively high nitrogen content in the no. 6 fuel oil. NO emissions were generally lower with less excess oxygen or excess air (see Figures 2 and 3).

4. Grayish white, powdery deposits were observed on boiler surfaces when blends with used lubricating oil were fired. These deposits are believed to be from the additives contained in the used lubricating oils. Since they were easily blown off during normal firing of other fuel blends, they do not appear to pose any long-term boiler deposit problem. (Because of the color of these deposits, smoke spot numbers were not reliable indications of smoke emission levels.)

5. The only adjustment required during these tests was the temperature of No. 6 oil/used lubricating oil blends because of their relatively high viscosities (see Table 9).

6. Ship's waste oil blends in both no. 2 and no. 6 oils tend to produce unstable and abruptly changing flame shapes.

7. Stable combustion was not achieved by steam atomizing no. 2 oil/JP-5 blends (believed to be due to rapid vaporization of JP-5 near the gun due to hot steam). However, stable combustion was achieved with a mechanical atomizing nozzle.

Tests Conducted at CEL

Three types of tests were conducted at CEL to supplement the results obtained by KVB described in the previous section. They consist of basic property measurements and boiler tests. These tests and the data obtained are described below.

Basic Properties of Fuel Blends. The physical and chemical properties of fuel blends are expected to be intermediate between those of their components. Once the properties of a waste oil have been determined to be suitable for boiler use, the exact values of the various properties of its blends are only of minor concern except for the API gravity (or simply gravity) and viscosity which directly affect boiler operations. The former is indicative of the approximate heating value of the blend (Figure 4, based on Reference 2), and the latter affects the flow rate and is therefore related to burner adjustments. Both gravity and viscosity may also be used as indicators of the proportion of waste oil in the blend. A combination of 18 blends obtained from eight kinds of oils was therefore prepared and measured for their gravities and viscosities, using a hydrometer and a Saybolt viscosimeter. The results are tabulated in Table 12.

The tabulated values of gravity and viscosity of these blends are intermediate between those of their components, but the variations are not linear with concentration. These variations exist because of the built-in nonlinearity in the definition of gravity and the nonlinear behavior of viscosity inherent with the oil. The nonlinearity of gravity may be removed simply by replacing it with specific gravity from which it is defined. Specific gravity is as readily measurable a quantity as the API gravity and is physically meaningful.

The nonlinearity of viscosity may be remedied by using the chart as shown in Figure 5 (Ref 35). When the viscosities of two oils are known, the viscosity of their blend may be estimated by drawing a straight line between the viscosities and reading the resultant viscosity at the intersection of this line and the vertical line representing the volume fractions of the two oils. To illustrate, the measured viscosities of the blends of no. 2 oil and used lubricating oil given in Table 10 are also plotted on Figure 5, which shows that the measured viscosities of the blends are slightly higher than those predicted from the line. For boiler operations, this accuracy is considered satisfactory. The numerical results are compared below:

Used Lube Oil Fraction (% by Volume)	Blend Viscosity, SUS* @ 100°F	
	Measured	Predicted
5	38	37
10	39	38.6
20	43	42.2
30	50	47.4

Tests in the CEL 30-hp Boiler Facility. This facility is a 2-pass, package type, on-off modulated, fire tube boiler with a mechanical atomization nozzle. The overall arrangement of this facility is shown schematically in Figure 6, and a pictorial view is shown in Figure 7. A number of waste oil/no. 2 fuel oil blends were tested using this facility. The blends were prepared by recirculating measured volumes of the components in a 55-gallon drum, using a 30 gpm centrifugal pump. Thorough mixing could be achieved in 2 minutes for a 10-gallon batch. Each blend was fired in the boiler immediately after it was prepared. Although no effort was made to determine the long-term stability of the blends, separation or stratification was not expected.

For the tests conducted here, a 9-gph nozzle and 100-psig atomization pressure were used. During startup, the boiler was fired at full load with no. 2 fuel oil, and the burner air was adjusted to achieve 5% excess oxygen in the stack gas. No subsequent burner adjustment was made when fuel blends were fired. The blends were tested in the boiler for approximately 1 hour each at full load. The light-off and steady state burning behavior were observed. When steady-state conditions were reached, the following measurements were made: stack gas excess oxygen, fuel firing rate, and Bacharach smoke spot number. The test results are summarized in Table 13.

*Saybolt Universal Seconds.

Generally speaking, with the given nozzle, the fuel flow rate tended to increase with the waste oil concentration, even though the viscosity was increased. Because of the fixed setting for burner air (corresponding to 5% excess oxygen when no. 2 oil is fired at full load), this increased fuel flow resulted in air deficiencies at times; consequently, smoke was visible from the stack. Later, after completion of the tests in Table 13, it was found that satisfactory, clean firing could be achieved conveniently by readjusting the burner air flow. That is, all the problems described under remarks in Table 13 could be resolved simply by burner air adjustment. Also, it was found that if an 8.5-gph nozzle was used in place of the original 9.0-gph nozzle, excess oxygen levels as low as 3% with a Bacharach smoke spot number of 2 could be attained when waste oil blends were fired. These observations suggest that changing the nozzle size in order to limit the fuel flow, and adjusting the burner air intake may be required for certain situations.

Tests in the CEL 200-hp Water Tube Boiler Facility. These tests were conducted to determine the maximum extent of the effects of the waste oils on combustion. For these tests, a variety of waste oils was obtained and burned (without blending) in the CEL boiler test facility. This facility is a 200-hp (7-MBtu/hr) water tube boiler with a rotary cup burner originally designed to burn no. 5 fuel oil. The boiler was actually a part of the steam plant at CEL, but it had not been used for many years. As a matter of opportunity, it was reactivated and modified for the sole purpose of testing boiler fuels.

The original fuel supply system was modified by adding four more fuel tanks so that a maximum of five different kinds of fuels could be stored and from which different kinds of fuel could be supplied one at a time to the burner. The arrangement of this system is shown schematically in Figure 8. It was possible to utilize the steam produced most of the time during the tests; steam dumping was occasionally necessary when an excess amount was produced. A muffler was installed at the steam vent to reduce the noise level during steam dumping.

The stack gas was continuously monitored for O_2, CO, and NO concentrations. A specially constructed instrumentation package was used for this purpose. This package, the boiler front end, the burner, and the weighing tank for flow rate measurements are shown in Figure 7.

A series of six tests was conducted using the existing no. 5 fuel oil and locally available waste oils. During each of these tests, the firing rate, oil temperature, and the burner air flow at each firing rate were varied to observe any operational limitations. These ranges and the data obtained are summarized in Table 14. In all, a total of 48 boiler operating hours were logged and approximately 1,600 gallons of oil were consumed. During these tests, no unexpected difficulties were encountered. It is to be noted that during the last test when contaminated no. 2 fuel oil was burned, unstable flame caused several shutdowns. This was due to the much lower viscosity of no. 2 oil compared to no. 5 oil for which the burner was designed. But this result serves to show the wide range of oils that can be used by such a burner. In reality, one should pay attention to using an oil with a viscosity not significantly different from that for which the burner was originally designed.

DISCUSSION

As shown in Figure 4, the heating value of an oil may be estimated from its specific gravity, γ (or API gravity). Specific gravity is also a convenient means to determine the concentrations of the components in a blend, as follows:

$$\gamma = \gamma_1 f_1 + \gamma_2 f_2$$

where γ_1 and γ_2 are, respectively, the specific gravity of components 1 and 2 having volume fractions (or concentrations) f_1 and f_2. Since, by definition

$$f_1 + f_2 = 1$$

we have,

$$f_1 = \frac{\gamma - \gamma_2}{\gamma_1 - \gamma_2}$$

Therefore, once γ, γ_1, and γ_2 are measured with an ordinary hydrometer, the amount of waste oil in a blend may be readily calculated.

The viscosity of an oil affects the flow rate and, consequently, the spray pattern for a given burner nozzle. In order to minimize any burner modification that may be required for firing waste oil blends, the viscosity of a blend must be maintained as close as possible to that of the fuel oil which is regularly used by the burner. This may be achieved by adjusting the temperature of the blend. The temperature variation of viscosity of typical fuel oils may be obtained by using the "Viscosity-Temperature Charts for Liquid Petroleum Products" recommended in ASTM D-341. Combining this and Figure 5, a working chart is proposed for determining the approximate operating temperature of fuel oil blends. This chart is shown in Figure 9.

Figure 9 consists of two separate graphs: the one on the left is used to determine the viscosity of a blend of two oils of different viscosities (all in SUS at 100°F) and the one on the right gives the temperature variation of viscosity for oils whose viscosities at 100°F are known. The use of these graphs is illustrated in the following example.

EXAMPLE

A burner is designed for burning a type of heavy fuel oil having viscosity of 1,000 SUS at 100°F. This oil is heated to 180°F to achieve satisfactory firing. A light waste oil on hand, which has a viscosity of 50 SUS at 100°F, will be blended into the heavy fuel oil to supplement the boiler fuel. In order to fully utilize this light waste oil, its concentration in the blend is determined to be 30%. What is the satisfactory operating temperature of this blend?

From the right-hand side graph of Figure 9, along the line labeled 1,000 SUS, we find that the viscosity of this oil at 180°F is 115 SUS. From the left-hand side graph, the viscosity of a blend of 30% waste oil is approximately 300 SUS. Again on the right-hand side of the graph, along the line labeled 300 SUS, we find that to attain 115 SUS the oil should be heated to 135°F. This is shown in the graphical construction.

CONCLUSIONS

1. Significant quantities of waste oils are routinely generated Navywide. Of all the waste oils the Navy generates, greater than 96% may be regarded as potential boiler fuels.

2. Between 4.9% and 12.8% of the total Navy requirements for natural gas, liquefied petroleum gases, and fuel oils may be met by use of the Navy-generated waste oils. Based on the FY-77 Navywide average cost of fuel oils, this means an annual fuel bill reduction of $8.7M/yr to $22.7M/yr.

3. Navy waste oils may be successfully fired in boilers by blending them into regular fuel oils at concentrations up to 100% if the waste oil is reasonably free of water and solid contaminants.

4. No special modificaton to burner equipment is required to fire waste oil blends. Minor adjustments are sometimes necessary, however, to correct unstable combustion and smoke emissions. These adjustments may be considered a routine part of boiler operations.

5. Straight used lubricating oils may be satisfactorily fired. Because of the relatively high ash content (approximately 2%, usually from the noncombustible additives in the oil), long-term firing of straight used lubricating oils may result in extra maintenance requirements or efficiency degradation due to ash accumulations on heat transfer surfaces (although the type of ash observed so far was loose and could be blown off easily).

6. Other than relatively high ash accumulation when firing blends of high concentrations of used lubricating oil, no apparent emission problem was encountered. Therefore, no special provisions will be required to monitor the stack gases. In order to insure efficient boiler operations, oxygen may be the only critical item for stack gas monitoring.

7. Viscosity appears to affect burner operations the most in both flow rate and spray pattern. To minimize such effects, the viscosity of a blend should be maintained as closely as possible to that of the regular fuel oil. This may be achieved by adjusting oil temperature (especially when heavy oils are fired).

8. Unstable combustion may be encountered in burning ship's waste oils. Since the majority of the Navy waste oils is ship's waste oil, further testing will be required in order to successfully utilize this energy resource.

RECOMMENDATIONS

Short-term test results reported here on batch blended, homogeneous waste oil/fuel oil mixtures show that they are substantially the same as regular fuel oils. No special modification to burner equipment is needed although minor adjustments are sometimes necessary to achieve efficient combustion. In view of the large quantities of waste oils the Navy generates, tests in in-service boilers must be conducted to determine any long-term effects to boiler equipment. The results will enable the development of guidelines to effectively utilize this energy resource.

Schemes other than batch blending must also be investigated.

At present, two locations are recommended for conducting these tests:

(1) Naval Weapons Center, China Lake. Boilers use heavy fuel oil (no. 6) as the primary fuel. NWC has an estimated potential of generating 2,500 gal/mo of lightweight waste oils. This location is ideal for testing lightweight waste oil blended into heavy fuel oil. An in-line blending scheme can be examined during these tests.

(2) Naval Air Station, Miramar. Boilers use light fuel oil (no. 2 or diesel) as the primary fuel. The nearby San Diego Naval Station generates approximately 2×10^6 gal/yr of light waste oils recovered from ship's oily waste which is more than enough to supply the total fuel requirements of the Station. This location is ideal for testing ship waste oils. Because of the nature of the facility and the availability of the oils, burning tests of straight ship waste oils can be conducted here.

During the tests at the above two locations, in addition to fuel properties and combustion characteristics, fuel storage and handling requirements will also be investigated.

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Table 1. Waste Oil Generation (gal/yr) at Seven Navy Areas (Estimates for After 1975, Refs 11-17)

Navy Area	Type and Approximate Composition							
	Bilge & Ballast[a]	Transport & Shop[b]	Tank Cleaning[c]	Low Flash Fuel[d]	High Flash Fuel[e]	Turbine Engine Drainings	Solvents	Total
San Diego, CA	1,231,800	135,100	-	130,950	159,550	103,000	18,100	1,778,500
Norfolk, VA	4,920,000	238,500	300,000	12,000	-	-	43,500	5,514,000
Pearl Harbor, HI	7,361,000	477,800	76,500	20,600	-	12,200	141,200	8,089,300
Puget Sound, WA	89,400	212,300	66,200	4,800	15,500	-	11,000	399,200
Charleston, SC	1,121,600	90,000	-	-	260,800	-	4,600	1,477,000
Jacksonville/ Mayport, FL	2,025,800	218,500	-	36,500	-	17,400	147,900	2,446,100
Los Angeles/ Long Beach, CA	2,649,900	-	-	-	86,500	2,000	-	2,738,400
TOTAL (% of Total)	19,399,500 (86.44)	1,372,200 (6.11)	442,700 (1.97)	204,850 (0.91)	522,350 (2.33)	134,600 (0.60)	366,300 (1.63)	22,442,500 (100.0)

[a]Mixed fuels and lubes with negligible water.

[b]Used lubes and transmission oils.

[c]Fuel, grease, solvent, detergent, and others.

[d]Avgas, Mogas, JP-4 (flash point <140°F).

[e]JP-5, kerosenes, DFM (flash point >140°F).

Table 2. Waste Oil Generation (gal/yr) at Seventeen Navy Bases (Estimates for 1980, Refs 18-34)

Location	Type and Approximate Composition[a]							
	Bilge & Ballast	Transport & Shop	Tank Cleaning	Low Flash Fuel	High Flash Fuel	Turbine Engine Drainings	Solvents	Total
Sub Base, New London, CT	124,000	-	-	-	-	-	-	124,000
NAS Brunswick, ME	-	35,000	-	-	-	5,000	-	40,000
NSY Kittery, ME	91,000	4,300	-	-	-	7,500	-	102,800
NSY Philadelphia, PA	203,600	9,300	2,900	-	114,000	-	11,100	340,900
NS Roosevelt Roads, Puerto Rico	323,410	10,050	-	5,050	5,050	-	-	343,560
NAS Pensacola, FL	-	27,350	220,000	233,530	43,400	300	-	524,580
NAS Bermuda	500,000	39,800	-	800	1,000	800	600	543,000
NAS Adak, AK	50,290	23,490	-	11,900	61,150	3,000	3,000	152,830
NCBC Port Hueneme, CA	15,000	7,400	-	3,000	5,750	-	5,300	36,450
NATC Patuxent River, MD	50	12,410	-	3,000	22,400	5,540	1,000	44,400
NB & NAS Guantanamo Bay, Cuba	45,130	44,500	-	105,730	66,230	-	200	261,790

(continued)

Table 2. Continued

Location	Type and Approximate Composition[a]							
	Bilge & Ballast	Transport & Shop	Tank Cleaning	Low Flash Fuel	High Flash Fuel	Turbine Engine Drainings	Solvents	Total
Naval Activities, Italy	-	10,180	1,300	14,590	-	-	-	26,070
Naval Support Activity, Athens, Greece	262,690	14,900	-	-	40,000	-	-	317,590
Naval Activities, Spain	554,620	13,510	8,400	9,370	30,190	-	3,200	619,290
Naval Activities, Canal Zone	52,100	3,720	-	-	368,400	-	400	424,620
NAF, Atsugi, Japan	-	9,950	-	6,500	120,000	550	100	137,100
NS, Midway Island	5,330	4,240	-	25,670	-	-	-	35,240
TOTAL (% of Total)	2,227,220 (54.67)	270,100 (6.63)	232,600 (5.71)	419,140 (10.29)	877,570 (21.54)	22,690 (0.56)	24,900 (0.61)	4,074,220 (100.01)

[a]See Table 1 for description of contents.

Table 3. Summary of Data on Waste Oil Generations by Navy Shore Facilities

Type	Waste Oil Generations (gal/yr)			Percent of Total
	7 Areas (Table 1)	17 Bases (Table 2)	Total	
Light Waste Oils				
Bilge and Ballast	19,399,500	2,227,220	21,626,720	
High Flash	522,350	877,570	1,399,920	
Subtotal	19,921,850	3,104,790	23,026,640	86.84
Heavy Waste Oils				
Transport and Shop	1,372,200	270,100	1,642,300	
Tank Cleanings	442,700	232,600	675,300	
Turbine Drainings	134,600	22,690	157,290	
Subtotal	1,949,500	525,390	2,474,890	9.33
Low Flash Materials				
Low Flash Fuels	204,850	419,140	623,990	
Solvents	366,300	24,900	391,200	
Subtotal	571,150	444,040	1,015,190	3.82
TOTAL	22,442,500	4,074,220	26,516,720	99.99

Table 4. Comparison of GLO[a] Consumptions and Waste Oil Generations

Location	Waste Oil Generation		GLO MBtu/FY-77	Waste Oil / GLO (%)
	gal/yr	MBtu/yr[b]		
Seven Areas				
San Diego	1,778,500	241,367	2,136,936	11.30
Norfolk	5,514,000	748,325	5,594,322	13.38
Pearl Harbor	8,089,300	1,097,831	842,388	130.3
Puget Sound	399,200	54,179	2,129,328	2.55
Charleston	1,477,000	200,452	1,036,116	19.34
Jacksonville/Mayport	2,446,100	331,968	1,715,652	19.35
Los Angeles/Long Beach	2,738,400	371,640	1,015,752	36.58
Subtotal	22,442,500	3,045,762	14,470,494	21.05[c]
Seventeen Bases				
Sub Base, New London, CT	124,000	16,826	1,884,468	0.89
NAS Brunswick, ME	40,000	5,426	438,780	1.24
NSY, Kittery, ME	102,800	13,954	20,334	68.62
NSY, Philadelphia, PA	340,900	46,267	3,760,674	1.24
NS, Roosevelt Roads, Puerto Rico	343,560	46,626	35,484	131.4
NAS, Pensacola, FL	524,580	71,193	2,882,646	2.47
NAS, Bermuda	543,000	73,695	365,112	20.19
NAS, Adak, AK	152,830	20,742	1,124,742	1.84
NCBC, Port Hueneme, CA	36,450	4,948	262,134	1.89
NATC, Patuxent River, MD	44,400	6,025	55,014	1.45
NB and NAS, Guantanamo Bay, Cuba	261,790	35,528	2,012,220	1.77
Naval Activities, Italy	26,070	3,540	65,424	5.42
Naval Support Activity, Athens, Greece	317,590	43,103	49,002	87.96
Naval Activities, Spain	619,290	84,047	81,708	102.9
Naval Activities, Canal Zone	424,620	57,627	0	-
Naval Air Facility, Atsugi, Japan	137,100	18,605	460,104	4.05
NS, Midway Island	35,240	4,782	238,248	2.00
Subtotal	4,074,220	552,934	13,736,094	4.03[c]
TOTAL	26,516,720	3,598,696	28,206,588	12.76[c]

[a]Total consumption of natural gas, liquefied petroleum gases, fuel oils.

[b]Assumed 135,700 Btu/gal for waste oils (= 98% of the standard heating value of distillate fuels).

[c]Average.

Table 5. FY-77 Energy Consumption by Navy Shore Facilities

Type of Energy Used	Energy Consumption		Costs		
	MBtu	Percent of Total	Total ($)	Percent of Total	$/MBtu
GLO					
Natural gas	21,302,237	13.26	37,578,789	9.89	1.76
Liquid petroleum gases	341,162	0.21	1,505,394	0.40	4.41
Fuel oils	51,949,537	32.34	125,676,188	33.09	2.42
Subtotal	73,592,936	45.81	164,760,371	43.88	2.24
Electricity	84,631,930	52.68	209,742,341	55.22	2.48
Coal	1,750,377	1.09	2,417,938	0.64	1.38
Steam and hot water	669,692	0.42	2,920,668	0.77	4.36
TOTAL	160,644,935	100.00	379,841,327	100.01	2.36

Table 6. Waste Oil Generations Ashore

Location	GLO[a] Consumptions[b]		Waste Oil Generation (MBtu)	Waste Oil/GLO (%)	Worth[c] ($M)
	MBtu	%			
7 Areas and 17 Bases[d]	28,206,588	38.3	3,598,696	12.8	8.7
Navywide[e]	73,592,936	100.0	$3.6x10^6$	4.9	8.7
			$9.4x10^6$	12.8	22.7

[a]GLO = sum of natural gas, liquefied petroleum gases, and fuel oils.

[b]Consumptions are extracted from DEIS-II file for FY-77.

[c]$5.7x10^6$ Btu/bbl is assumed for waste oils and $2.42/MBtu is used to compute the worth of the oils.

[d]Actual data gathered.

[e]Last three columns represent lower and upper limits as estimated.

Table 7. Ship Waste Oils Generated and Sold to Contractor from San Diego Naval Station

Month	FY-77[a]	FY-78[a]
October	108,534	83,276
November	81,678	67,095
December	177,616	36,416
January	45,263	214,969
February	65,560	304,872
March	144,929	108,958
April	162,303	132,964
May	46,488	222,220
June	85,444	190,403
July	193,038	321,942
August	71,065	128,244
September	104,311	267,905
Total, gal	1,286,229	2,079,264
Energy Content, MBtu	174,560	282,186
Estimated Worth,[b] $	532,407	860,667

[a]Variations between months reflect a combination of seasonal changes and the availability of the contractor to haul the oils.

[b]Estimated worth is based on $3.05/MBtu for fuel oils paid by Miramar NAS during FY-77 and an estimated heating value of 5.7 MBtu/bbl for the waste oil.

Table 8. Economic Analysis

Items Affecting Economics	FY-77	FY-78
1. Energy consumed by MNAS, MBtu	242,998	266,353
2. Fuel bills paid by MNAS, $	725,839	510,491
3. Waste oil generated at SDNS, MBtu	174,560	282,186
4. Received from oil sales to contractor, $	285,543	524,789
5.[a] Waste oil deficiency (line 1 - line 3), MB	68,438	-0-
6. Cost of interruptible natural gas to supplement waste oils ($2.65/MB x line 5), $	181,361	-0-
7. Transportation cost of waste oil from SDNS to MNAS (7.37¢/MBtu[b] x lines 3 or 1), $	12,865	19,630
8. Savings to MNAS realizable (line 2 - line 6 - line 7), $	531,613	490,861
9. Net savings to Navy (line 8 - line 4), $	246,070	c

[a]Calculations for items 5 through 9 are based on use of waste oils up to the actual energy requirements given in line 1.

[b]1¢/gal.

[c]To avoid unnecessary confusions, the figure is not entered here. See text for explanations.

Table 9. Properties of Some of the Oils Tested

Properties	Fuel Oil			Heavy Shale Oil	Used Lube Oil	Ship's Waste Oil	Contaminated JP-5
	No. 6	No. 5	No. 2				
API Gravity	23		34	22	26.1	29.1	40.6
Heating Value (HHV, Btu/lb)	19150	18576	19560	18420	19270	19390	19770
Viscosity, SUS @ 100°F	324		35	150	527	60	31
Flash Point, °F	245		168	295	370	260	145
Water and Sediment, %	0.12	0.44	<0.1	1.0	<0.1	0.12	3.4
Carbon Residue (Ramsbottom), %	3.44		0.12	2.0	1.11	0.17	0.10
Copper Strip Corrosion	S.T.[a]		S.T.		S.T.	S.T.	S.T.
Carbon, %	86.61	85.02	86.11	85.8	85.08	86.18	86.05
Hydrogen, %	12.25	11.53	12.94	11.19	13.13	13.13	13.43
Nitrogen, %	0.24	0.33	0.022	1.95	0.074	0.008	0.004
Sulfur, %	0.28	1.31	0.082	0.46	0.44	0.081	0.086
Ash, %	0.016	0.032	<0.001	0.007	1.36	0.001	0.001
Oxygen, % by Difference	0.60	1.78	0.85	0.59	0	0.60	0.43
Vanadium, ppm	15		<0.04		N.D.	0.066	N.D.[b]
Iron, ppm	12		<0.06		23	0.11	0.35
Nickel, ppm	4.6		<0.1		0.8	0.055	0.017
Calcium, ppm	12		<0.2		6700	0.7	2.6

(continued)

Table 9. Continued

Properties	Fuel Oil			Heavy Shale Oil	Used Lube Oil	Ship's Waste Oil	Contaminated JP-5
	No. 6	No. 5	No. 2				
Magnesium, ppm	7.8		<0.5		30	0.27	0.26
Sodium, ppm	12		<2		Trace	N.D.	N.D.
Silicon, ppm	15		<2		22	1.0	0.50
Manganese, ppm	0.18		<0.004		7.5	0.023	0.024
Aluminum, ppm	3.2		<0.2		3.7	0.21	0.13
Barium, ppm	1		<0.4		26	1.8	0.56
Lead, ppm	<1.2		<0.5		19	<0.5	<0.5
Tin, ppm	0.11		<0.1		4.8	0.27	0.50
Molybdenum, ppm	0.027		N.D.		N.D.	N.D.	N.D.
Copper, ppm	0.059		<0.01		1.4	2.5	0.094
Silver, ppm	0.0034		<0.004		0.11	0.051	0.010
Zinc, ppm	0.54		<0.1		670	0.43	0.43
Titanium, ppm	0.086		<0.07		N.D.	0.11	0.047
Cobalt, ppm	0.66		N.D.		N.D.	N.D.	N.D.
Potassium, ppm	Trace		N.D.		N.D.	N.D.	N.D.
Chromium, ppm	0.042		<0.03		0.64	0.17	0.047
Strontium, ppm	0.082		N.D.		28	N.D.	N.D.
Boron, ppm	N.D.		<0.05		6.4	N.D.	N.D.
Phosphorus, ppm	N.D.		N.D.		1300	N.D.	N.D.
Cadmium, ppm	N.D.		N.D.		4.4	0.094	N.D.

[a]S.T. = Slight Tarnish.

[b]N.D. = None Detected.

Table 10. Waste Oil/Fuel Oil Blends Tested by Contractor (steam atomization nozzle was used except as noted)

Fuel Oil	Waste Oil	Waste Oil (%)		Gravity (°API)	Viscosity (SUS @ 100°F)	Remarks
		By Mass	By Volume			
No. 2	Used Lube Oil	5.03	4.8	33.5	38	
		10.0	9.5	33.2	39	
		20.0	19.1	32.4	43	
		30.0	28.6	31.7	50	
	Ship's Waste Oil	5.0	4.9	33.8	37	Flame unstable
		10.0	9.7	33.5	37	
		20.0	19.4	33.0	38	
		30.0	29.1	32.5	40	
	Contaminated JP-5	10.0	10.4	34.5	35	Could be successfully fired only with mechanical atomization
		20.0	20.8	35.0	35	
		40.0	41.7	36.4	35	
		60.0	62.5	42.1	31	
No. 6	Used Lube Oil	5.0	5.1	23.0	346	
		9.94	10.1	23.2	311	
		20.0	20.4	23.6	320	
		30.0	30.6	23.6	335	
	Ship's Waste Oil	5.0	5.2	22.7	281	Flame unstable
		10.0	10.4	23.4	233	
		20.0	20.8	24.5	163	
		30.0	31.3	24.8	150	
	Contaminated JP-5	4.9	5.5	23.9	218	
		10.0	11.1	24.6	153	
		20.0	22.3	26.9	89	
		30.0	33.4	28.9	62	

(continued)

Table 10. Continued

Fuel Oil	Waste Oil	Waste Oil (%)		Gravity (°API)	Viscosity (SUS @ 100°F)	Remarks
		By Mass	By Volume			
No. 2			0	34.0	36	Reference only (from Table 9)
No. 6			0	23.0	324	
Used Lube Oil			100	26.1	527	
Ship's Waste Oil			100	29.1	60	
Contaminated JP-5			100	40.6	31	

Table 11. Data Summary of Boiler Tests of Waste Oil Blends by Contractor (see Table 10) [An 80-hp fire tube boiler with a steam atomization nozzle was used except as noted.]

Blend	Firing Rate (10^6 Btu/hr)	Stack Temp. (°F)	O_2, Dry (%)	CO_2, Dry (%)	CO, Dry (ppm)	NO, Dry at 3% O_2 (ppm)	Bacharach Smoke Spot No.	Remarks
Blends With No. 2 Oil								
No. 2 (Base)	3.23	500	3.3	12.8	15	86	0	
No. 2 + 5% Used Lube Oil	3.24	485	3.4	12.9	15	80	0	More compact flames than no. 2 oil. Grayish white powdery deposits.
+ 10% Used Lube Oil	3.28	490	3.1	12.8	15	97	0	
+ 20% Used Lube Oil	3.25	470	3.3	12.6	5	77	0	
+ 30% Used Lube Oil	3.2	490	3.4	12.8	15	100	0	
+ 5% Ship's Waste	3.25	505	3.1	13.8	12	75	0	Periodic change in flame shape with abrupt changes in emissions, noise, and smoke. Ship's waste oil has no effect on smoke and NO.
+ 10% Ship's Waste	3.3	500	2.9	13.2	15	70	0	
+ 20% Ship's Waste	3.3	510	2.8	13.9	15	75	0	
+ 30% Ship's Waste	3.29	500	2.9	14.6	15	73	0	
+ 10% JP-5	3.3	475	2.7	13.2	15	51	0	Severe pulsation and vibration with steam atomization. Stable flames were obtained with mechanical atomization. Flames appear to be wispy and cloudy.
+ 20% JP-5	3.15	500	3.7	12.6	15	60	0	
+ 40% JP-5	3.28	500	3.0	13.3	15	46	3	
+ 60% JP-5	3.14	485	3.8	10.6	6	56	0	
Blends With No. 6 Oil								
No. 6 (Base)	3.23	540	3.2	13.5	15	263	4	
No. 6 + 5% Used Lube Oil	3.23	470	3.2	13.8	15	263	1	Fired at 200°F oil temperature. Slight tendency to produce sparklers at high concentrations. Flames are more luminous than no. 6 oil.
+ 9.9% Used Lube Oil	3.18	540	3.5	13.2	15	246	0	
+ 20% Used Lube Oil	3.14	500	3.8	12.6	15	215	0	
+ 30% Used Lube Oil	3.09	500	3.7	12.8	15	219	0	
+ 5% Ship's Waste	3.27	485	3.15	14.0	9	160	3	Unstable pulsating flames. Abrupt changes. Worse at high concentrations.
+ 10% Ship's Waste	3.3	515	3.1	14.0	10	196	2	
+ 20% Ship's Waste	3.2	520	3.4	14.0	12	189	2	
+ 30% Ship's Waste	3.19	525	3.5	13.8	18	201	2	
+ 4.9% JP-5	3.22	505	3.3	12.8	15	163	1	Flame shape changes periodically. Noisy at 30%. Flames were wispy and cloudy in appearance.
+ 10% JP-5	3.21	500	3.6	13.2	35	150	2	
+ 20% JP-5	3.21	510	3.45	11.6	21	138	2	
+ 30% JP-5	3.21	500	3.5	14.0	12	123	2	

Table 12. Gravity and Viscosity of a Matrix of Oil Blends

Oil Basis		Characteristics of Oil Blends With --					
		No. 2 Diesel Fuel		No. 2 Fuel Oil		No. 5 Fuel Oil	
Type	Volume Fraction (%)	Gravity[a] (°API)	Viscosity[b] (SUS)	Gravity[a] (°API)	Viscosity[b] (SUS)	Gravity[a] (°API)	Viscosity[b] (SUS)
No. 5 Fuel Oil	0	34.1	36	39.6	34.5	19.6	442
	5	33.5	37	38.7	35		
	10	33.1	38	37.5	37		
	20	31.3	41	35.5	40		
	30	29.9	47	33.7	44		
	40	28.5	55	31.6	51		
	50	26.7	68	29.8	60		
	100	19.6	442	19.6	442	19.6	442
New Lube Oil (SAE30)	0	34.1	36	39.6	34.5	19.6	442
	5	33.6	37	38.8	36	20.0	445
	10	33.3	39	38.3	37	20.2	462
	20	32.3	42	36.6	40	20.7	479
	30	31.6	50	35.5	44	21.3	505
	40	30.6	58	34.0	53	21.9	527
	50	29.6	72	32.5	66	22.7	558
	100	25.5	674	25.5	674	25.5	674
Used Lube Oil (Diesel Shop)	0	34.1	36	39.9	34.5	19.6	442
	5	33.8	37	39.0	36	19.9	443
	10	33.6	39	38.4	37	20.2	445
	20	32.7	43	36.9	40	20.9	451
	30	31.8	46	35.5	45	21.8	454
	40	31.0	53	34.2	51	22.5	457
	50	30.2	67	33.0	62	23.1	461
	100	26.7	470	26.7	470	26.7	470

(continued)

Table 12. Continued

Oil Basis		Characteristics of Oil Blends With --					
		No. 2 Diesel Fuel		No. 2 Fuel Oil		No. 5 Fuel Oil	
Type	Volume Fraction (%)	Gravity[a] (°API)	Viscosity[b] (SUS)	Gravity[a] (°API)	Viscosity[b] (SUS)	Gravity[a] (°API)	Viscosity[b] (SUS)
Used Lube Oil (SAE10)	0	34.1	36	39.6	34.5	19.6	442
	5	33.9	36	39.3	35	20.0	425
	10	33.7	38	39.0	35	20.3	412
	20	33.3	41	38.9	39	21.6	377
	30	32.6	45	38.4	41	22.2	342
	40	32.0	48	37.9	46	23.2	318
	50	31.7	58	37.5	52	24.3	287
	100	39	196	29	196	29	196
Contaminated Distillate Fuels	0	34.1	36	39.6	34.5	19.6	442
	5	34.6	36	39.5	35	20.1	368
	10	34.5	37	39.0	35	21.1	299
	20	34.6	37	39.0	36	23.0	210
	30	34.7	38	38.6	36	24.6	158
	40	34.8	38	38.3	37	26.1	141
	50	35.0	40	37.9	38	27.9	90
	100	36	44	36	44	36	44
Mixed Lubricants and Hydraulic Oils	0	34.1	36	39.6	34.5	19.6	442
	5	34.0	36	39.4	35.0	20.3	430
	10	34.0	38	38.9	36	20.9	425
	20	33.6	40	38.3	38	22.2	408
	30	33.4	46	37.4	42	23.1	376
	40	32.5	52	36.5	48	24.4	367
	50	32.1	60	35.7	56	25.6	353
	100	32	270	32	270	32	270

[a]Measured at room temperature and corrected to 60°F or 15.6°C.

[b]Measured at 100°F or 37.8°C.

Table 13. Data Summary of Boiler Tests of Waste Oil/No. 2 Oil Blends [CEL 30-hp boiler facility with a 9-gph pressure atomization nozzle was used.]

Waste Oil % Vol.	Gravity °API @ 60°F	Viscosity SUS @ 100°F	Firing Rate		Stack Gas		Remarks[a]
			Gal/Hr	Lb/Min	% O_2 (Wet)	Bacharach Smoke Spot No.	
0	39.6	34.5	8.96	1.03	5.2	1	Baseline test.
New SAE 30 Lube Oil (25.5 °API, 674 SUS)							
30	35.5	44	9.77	1.12	3.8	4	
40	34.0	53	10.30	1.20	2.9	7	Stable smokey burn.
50	32.5	66	10.71	1.33	2.1	8	Poor lightoff, puffing & smoking.
Used Diesel Lube Oil (26.7 °API, 470 SUS)							
30	35.5	45	9.59	1.12	4.1	2	
40	34.2	51	9.94	1.22	3.5	4	Lightoff puffy, stable burn.
50	33.0	62	10.66	1.32	2.3	7	Lightoff bad, smokey burn.
Used SAE 10 Lube Oil (29.0 °API, 196 SUS)							
30	38.4	41	9.54	1.13	4.2	3	Mild puffing.
40	37.9	46	9.72	1.17	3.9	5	Mild puffing, smokey burn.
50	37.5	52	10.30	1.30	2.9	7	Lightoff poor, smokey burn.
Mixed Lube and Hydraulic Oils (32.0 °API, 270 SUS)							
30	37.4	42	9.59	1.14	4.1	3	
40	36.5	48	9.90	1.22	3.6	6	Lightoff OK, smokey burn.
50	35.7	56	10.44	1.38	2.6	7	Lightoff OK, smokey burn.

[a]Lightoff OK and stable burn was usually achieved except where noted.

Table 14. *Data Summary of Boiler Tests of Straight Waste Oils*
[CEL 200-hp boiler test facility with an ARC-144, size 7, rotary cup burner was used.]

Fuel	Firing Rate (lb/min)	Total Time (hr)	Total Fuel (gal)	Excess O_2, Dry (%)	CO, Dry (ppm)	NO, Dry at 3% O_2 (ppm)	Smoke[a]	Remarks
No. 5 Fuel Oil (Referee) Normal Operation	1.90 to 6.46	12	400	12.8 to 3.1	30 to >1000	130 to 340	If O_2 < 4, smoke R > 0.5	Fuel temperature varied from 95°F to 127°F.
Used Lube Oil (Dried)	2.88 to 6.00	6	200	11.3 to 4.3	22 to 160	130 to 370	Slight white haze	Fuel temperature varied from 110°F to 120°F.
Used Lube Oil (4.4% Moisture)	2.06 to 6.19	8	250	13.0 to 5.2	26 to 270	122 to 320	Smoking at low fire	Fuel temperature varied from 85°F to 126°F. Smoking at low fire, increased as fuel temperature increased.
Residual Shale Oil	2.85 to 6.20	12	400	11.1 to 4.9	28 to 120	620 to 830	Slight smoking at low fire, R = 1	Fuel temperature varied from 106°F to 157°F. Low temperature firing resulted in poor spray pattern from nozzle (carbon buildup observed on refractory near nozzle).
No. 5 Fuel Oil (Referee) Low Excess Air Operation	Low Fire to High Fire	6	200	7.6 to 4.1	0 to 370	210 to 340	Slight haze at high fire	Fuel temperature approximately 100°F. Tests to obtain reduced variation in excess oxygen over firing range.
Contaminated No. 2 Fuel Oil	1.90 to 5.58	4	150	7.2 to 4.15	20 to 55	110 to 160	Slight smoke at high fire	Fuel temperature at 85°F. Unstable flame caused several shutdowns.

[a] R = Ringelmann number, 1 lb/min ≈ 0.15 gal/min.

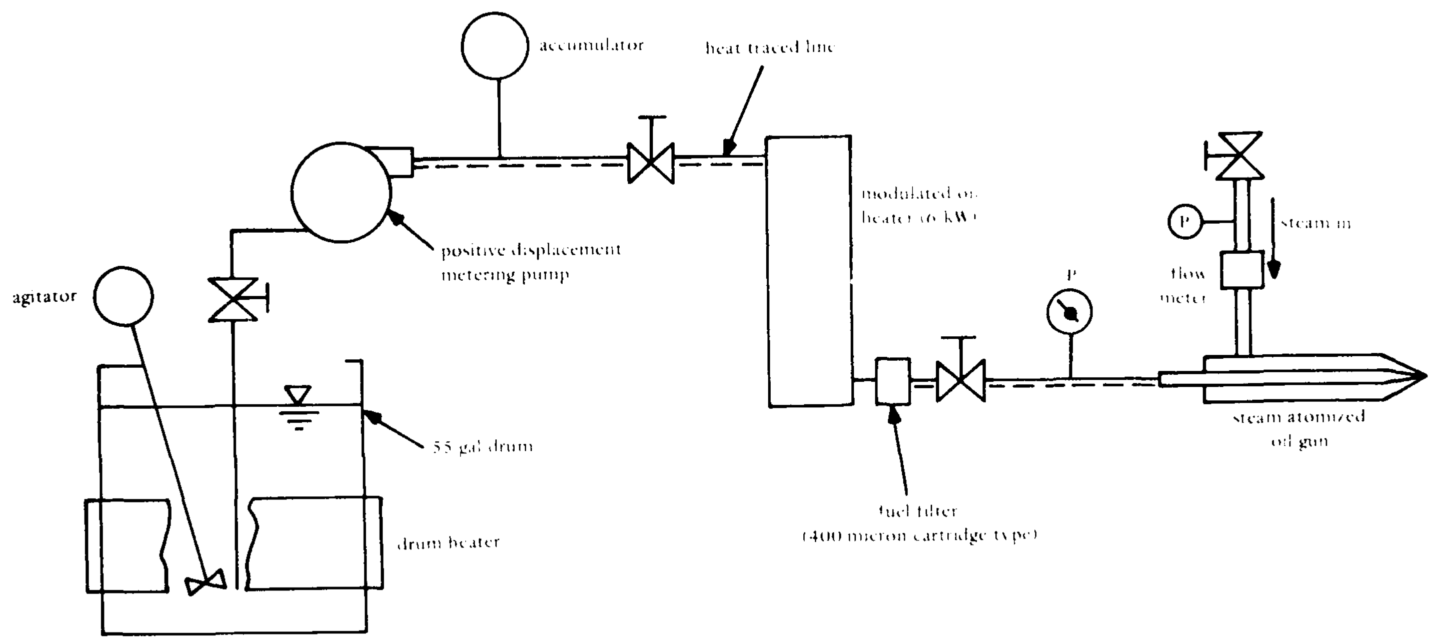


Figure 1 Fuel system for tests at contractor's facility.

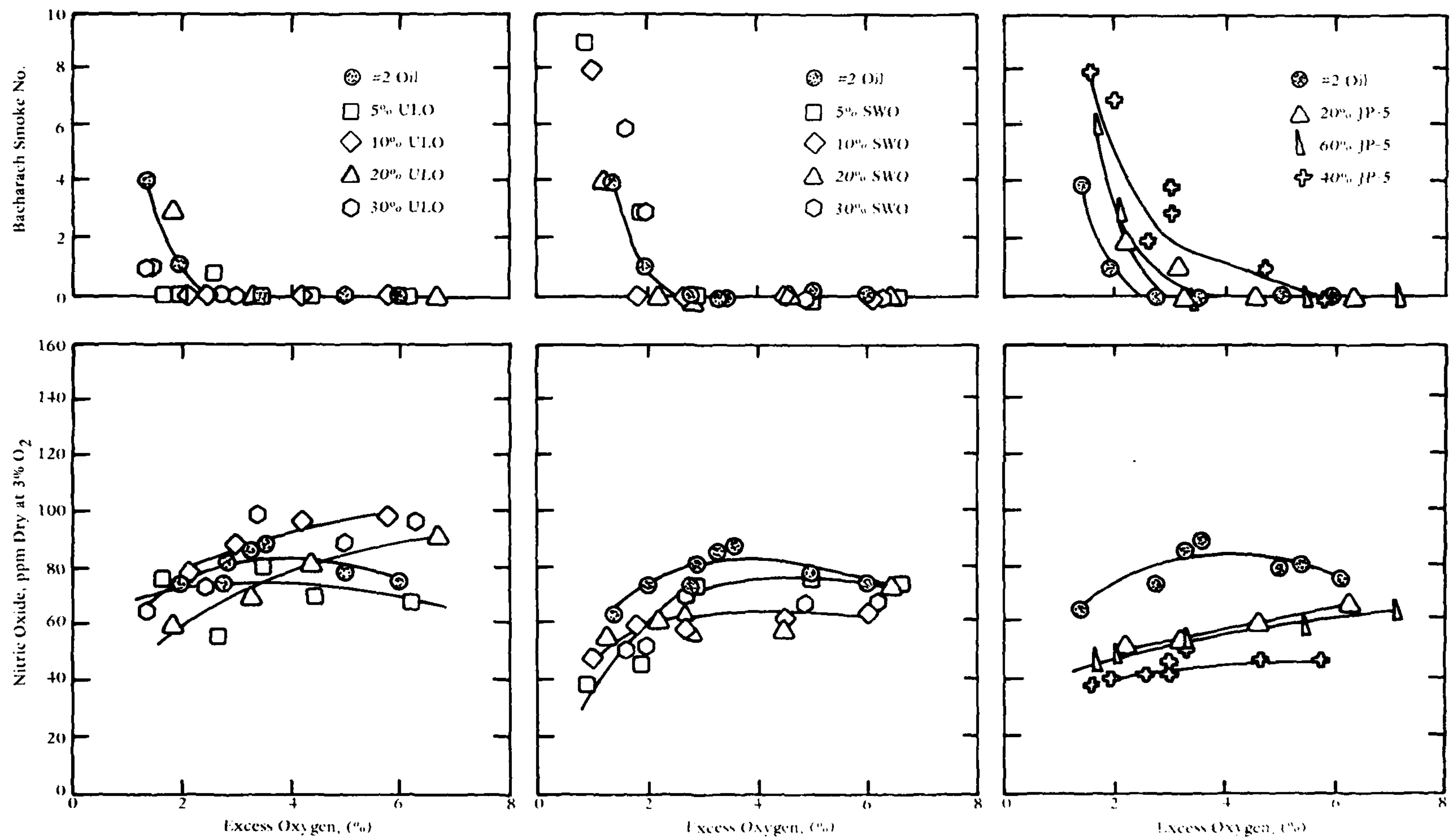


Figure 2. Smoke and NO emissions from burning of waste oil with no. 2 oil.
(ULO = used lubricating oil, SWO = ship's waste oil,
JP-5 = contaminated JP-5).

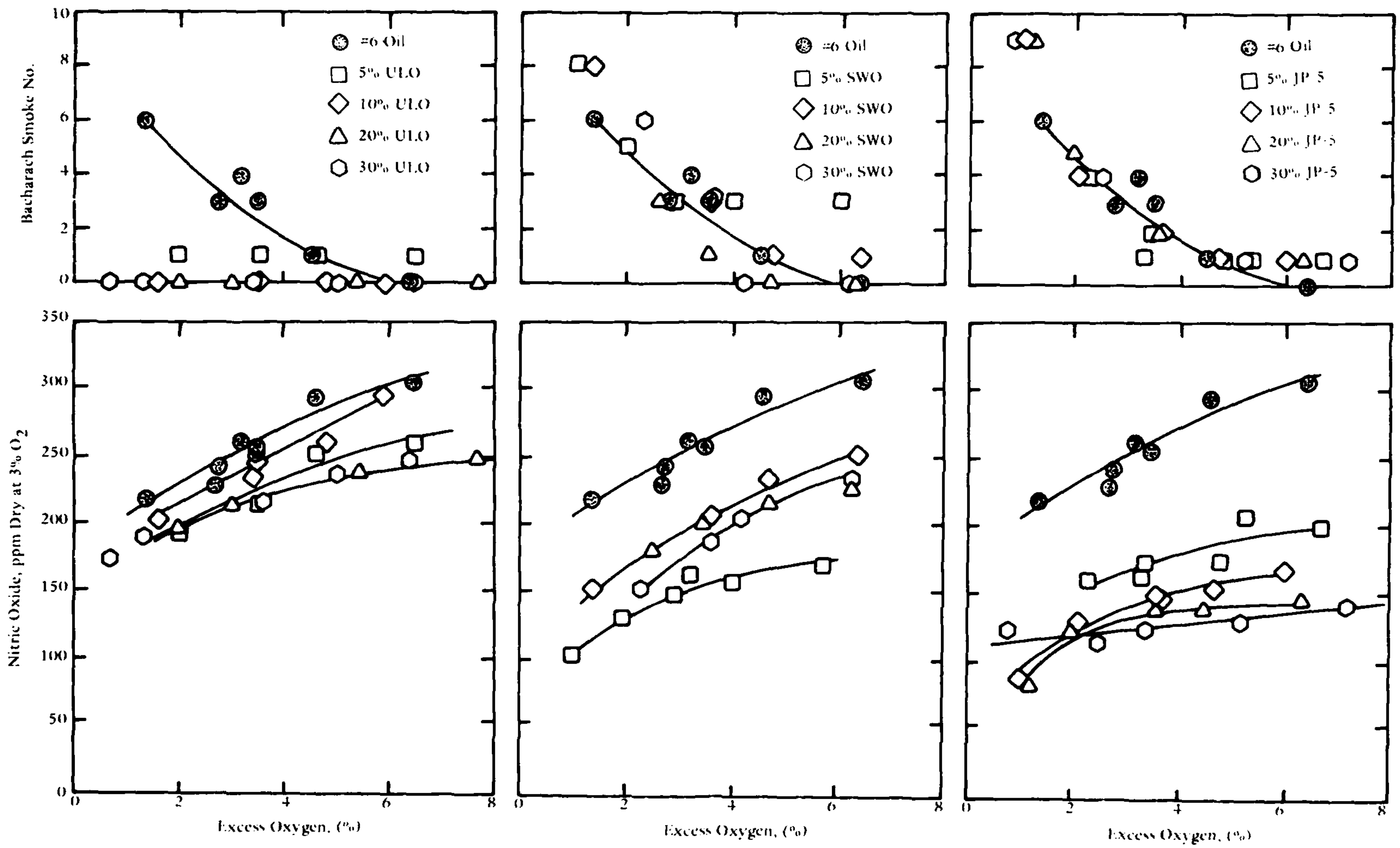


Figure 3. Smoke and NO emissions from burning of waste oil with no. 6 oil. (ULO = used lubricating oil, SWO = ship's waste oil, JP-5 = contaminated JP-5).

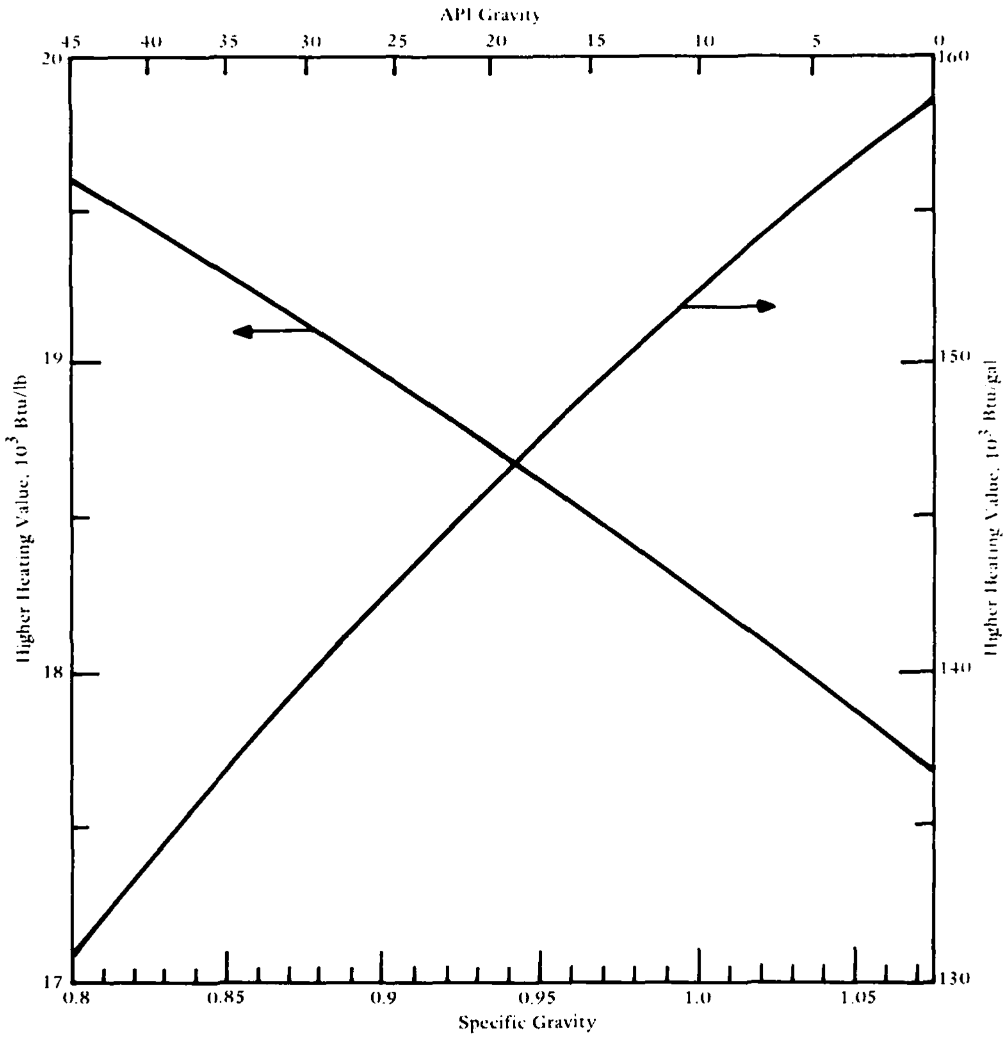


Figure 4. Relationship between higher heating value and specific gravity of petroleum oils at 60°F.

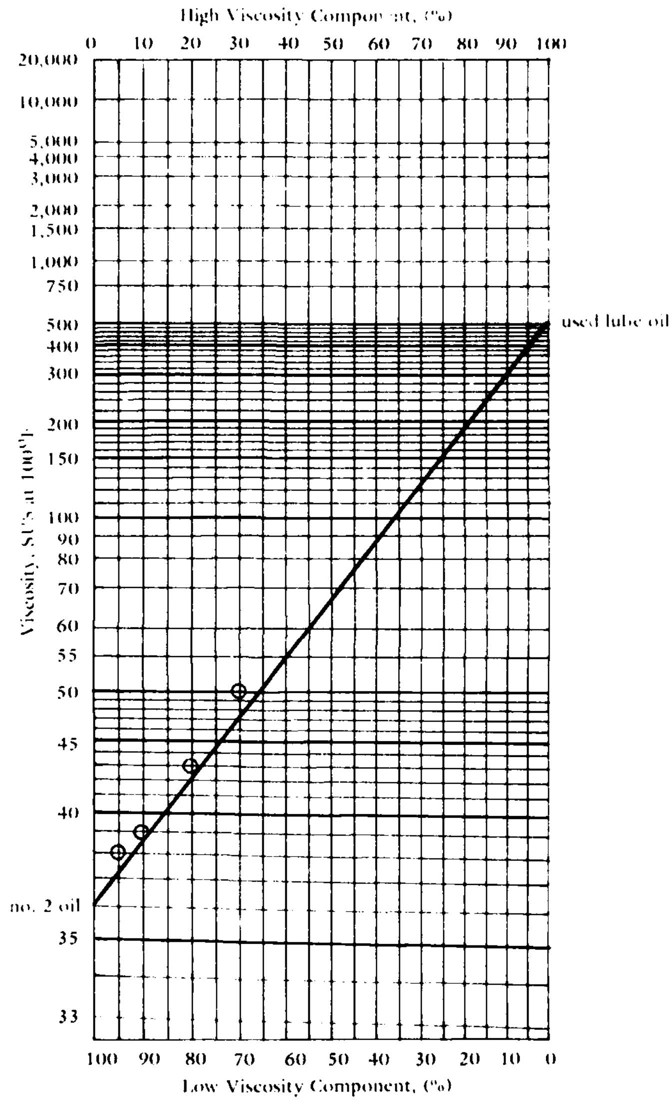


Figure 5. Determining the viscosity of blends.
(Data points are from Table 2.)

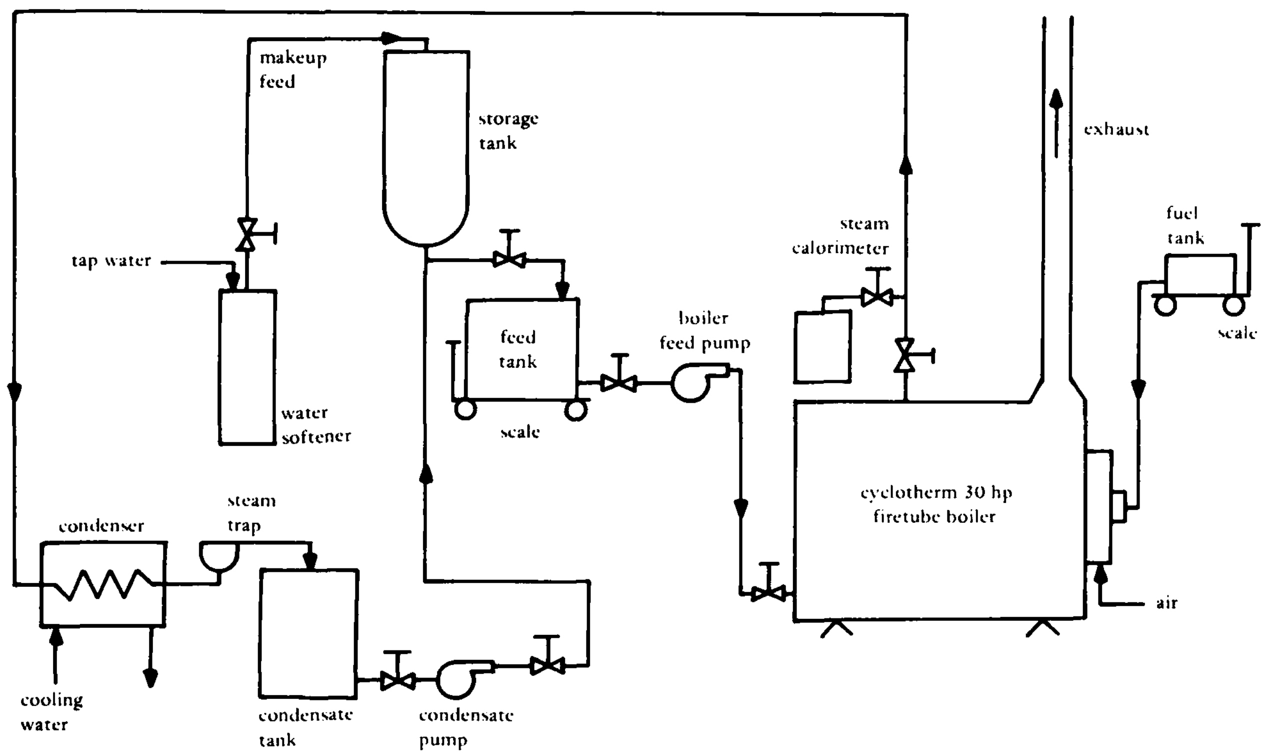
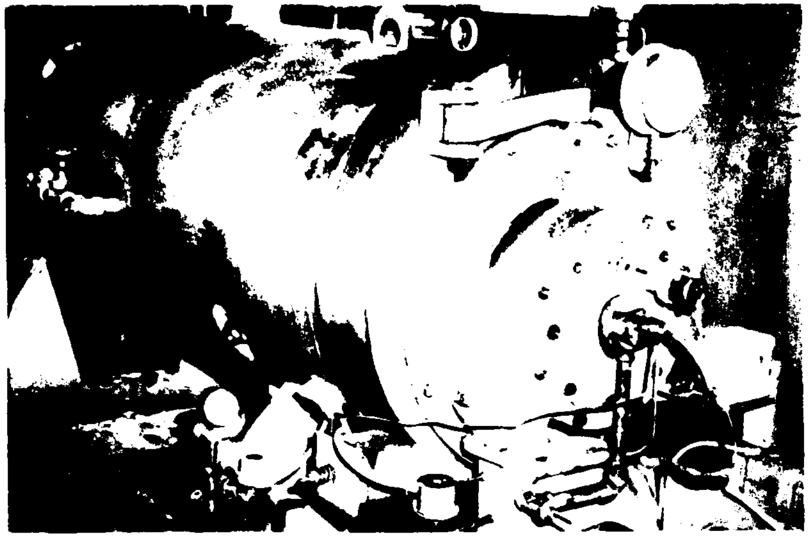
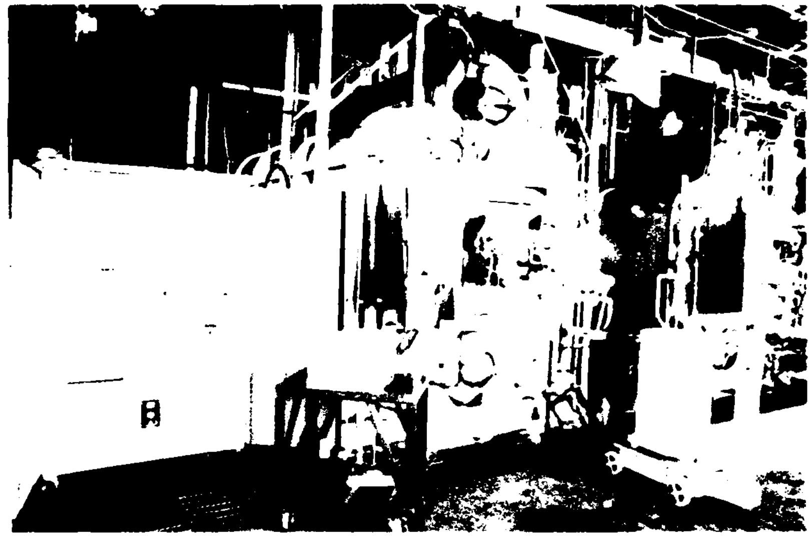


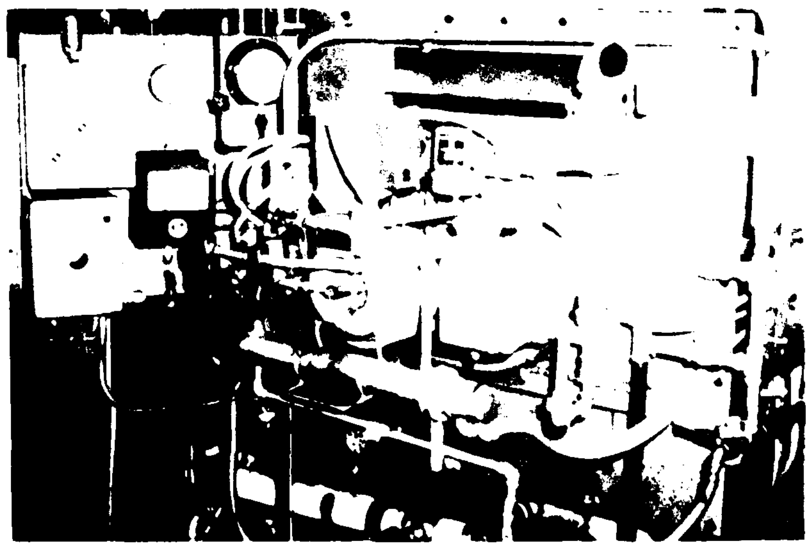
Figure 6. Test setup of the CEL 30-hp fire tube boiler.



(a) 30-hp fire tube boiler.



(b) 200-hp water tube boiler.



(c) Front face of 200-hp test boiler.

Figure 7. CEL boiler test facilities.

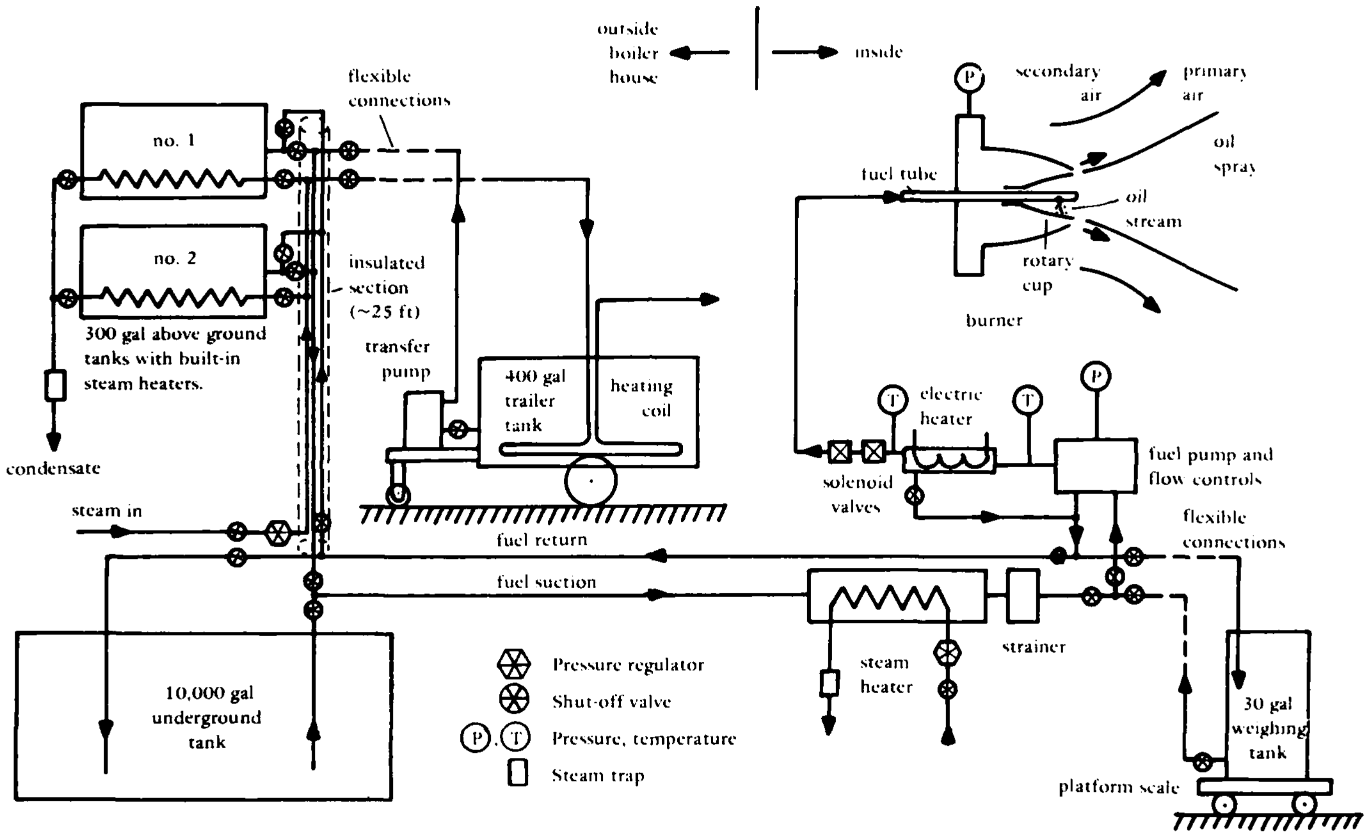


Figure 8. Fuel handling system for the CEL 200-hp water tube boiler test facility (schematic).

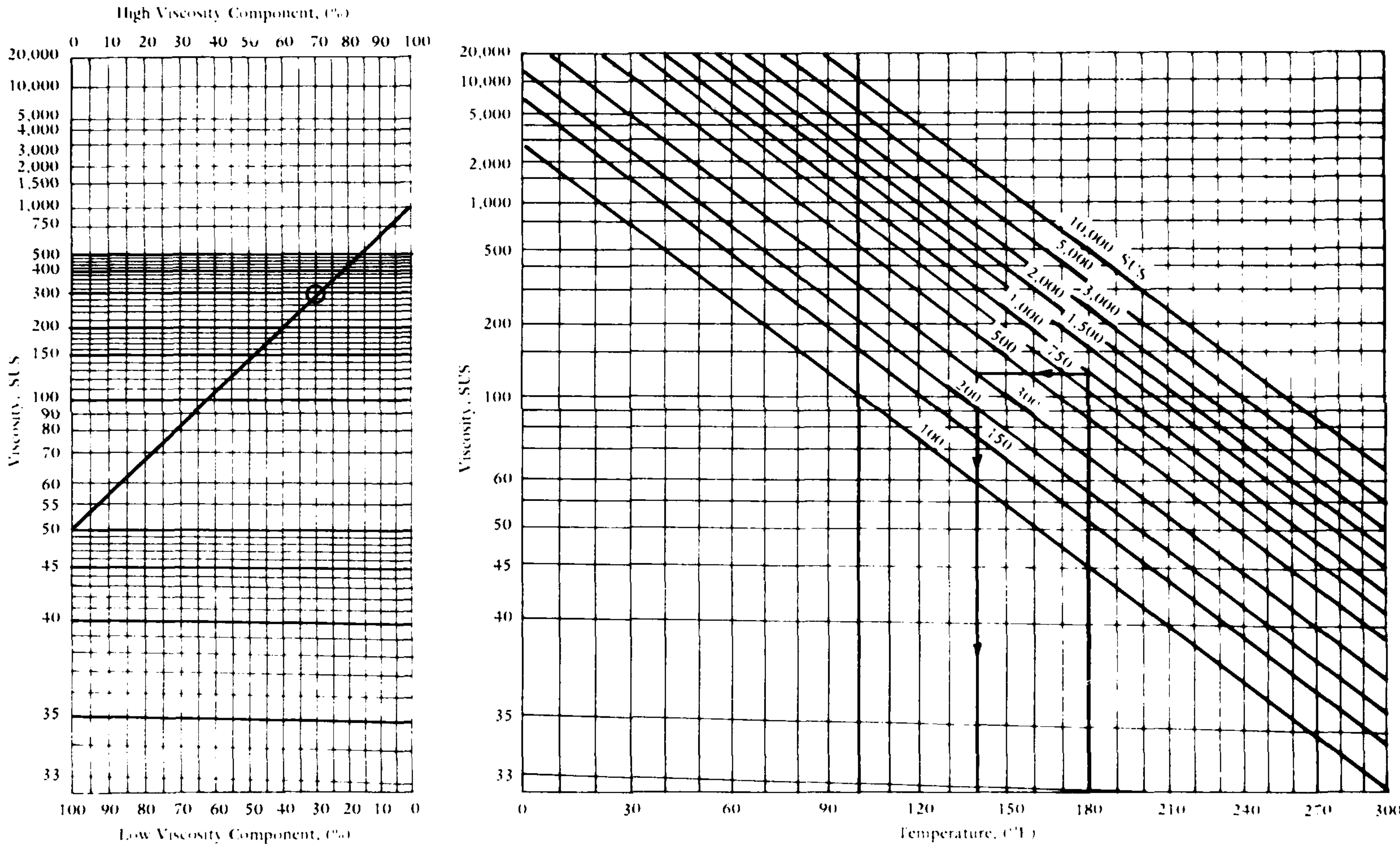


Figure 9. Charts for determination of firing temperatures for blending fuels

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